Developing an Integrated Urban Modeling System for WRF

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Research Application Laboratory/NCAR

Outline

- **Issues associated with urbanization**
- **Overview of an urban modeling framework**
- **Examples of applying this modeling system**

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NCEP EMC Seminar, Camp Springs, 18 October 2005

Urbanization Issues

- Nearly 300 cities have a million or more inhabitants
- Adverse urbanization effects:
  - Poor air quality, toxic contaminant dispersal
  - Deterioration of visibility
  - Adverse impacts on human health
  - Damage to agriculture and ecosystems
  - Water and energy supply/demand
  - Impact on climate (ozone and aerosol, greenhouse radiation budget)
  - Emergency response

Air pollution is not a local problem

March - December 2004 TERRA/MOPITT images

Concentration of carbon monoxide (CO) at 15,000 feet

Red colors: highest levels of CO (450 parts per billion)

Blue: lowest levels of CO (50 ppb)

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

John Gille, ACD/NCAR

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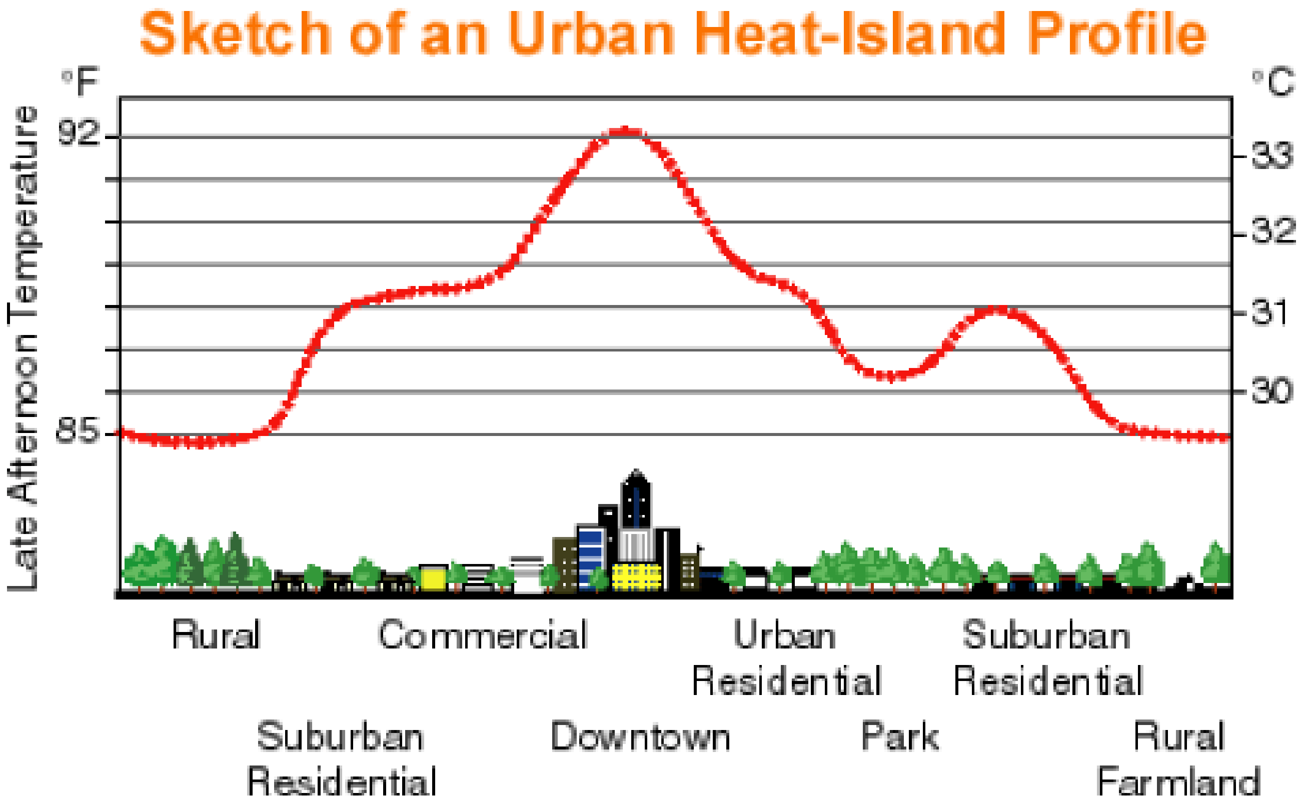
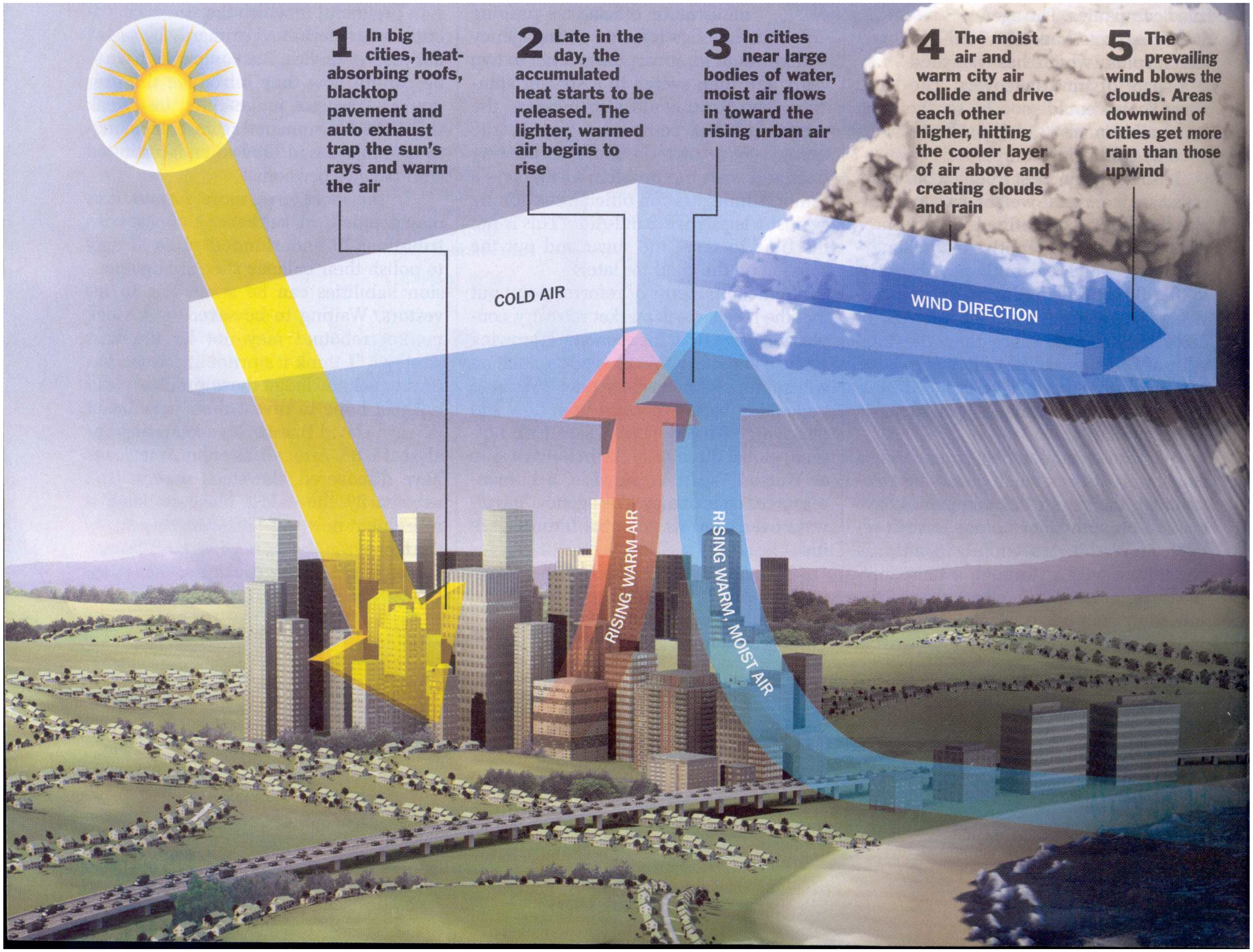


Temperatures in most cities are warmer than suburban rural areas.

Urban Heat Island Phenomena

- Increase the demand for energy
  - 1/6 of the electricity consumed in US is used for cooling purposes ($ 40 billion /year)
- Higher air temperatures increase the amount of ground level ozone, or smog
- May enhance heat waves within cities.
  - The mortality rate during a heat wave increases exponentially with the maximum temperature, an effect that is exacerbated by the urban heat island
  - European Heat Wave of 2003: as many as 40,000 people died in Europe



From TIMES magazine, Aug 2003

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Embrace the New-era of Urban Modeling and Application

- Urban problems can only be addressed in mesoscale/fine-scale modeling framework
- We can now bridge the gap between traditional mesoscale (~ 10 km) and fine-scale urban modeling (~ 10 m)
  - NWP models running at 1-km grid spacing
  - Availability of new data at urban scales
  - Techniques to couple NWP and CFD-type models
- Pathway to decision support systems and decision makers

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Integrated Urban Modeling Framework

urban land use characteristics

Surface emission sources

High-res land data assimilation system

Fine-scale atmospheric analysis (4DDA, VDRAS)

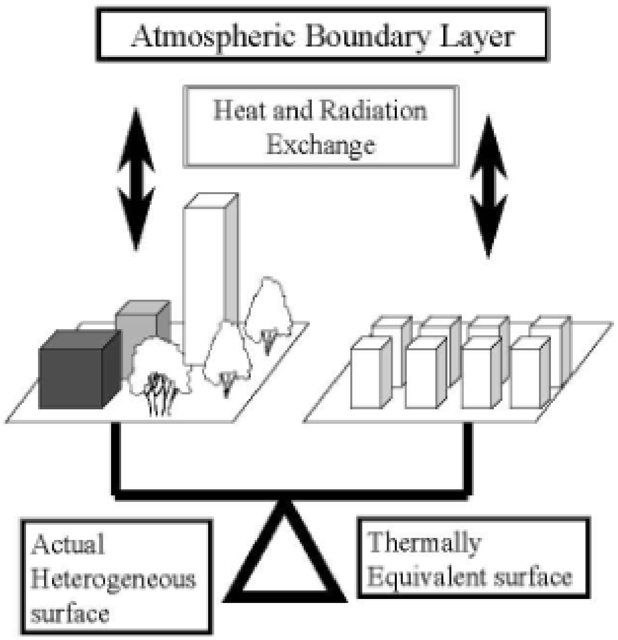
WRF/Noah/Urban coupled modeling system

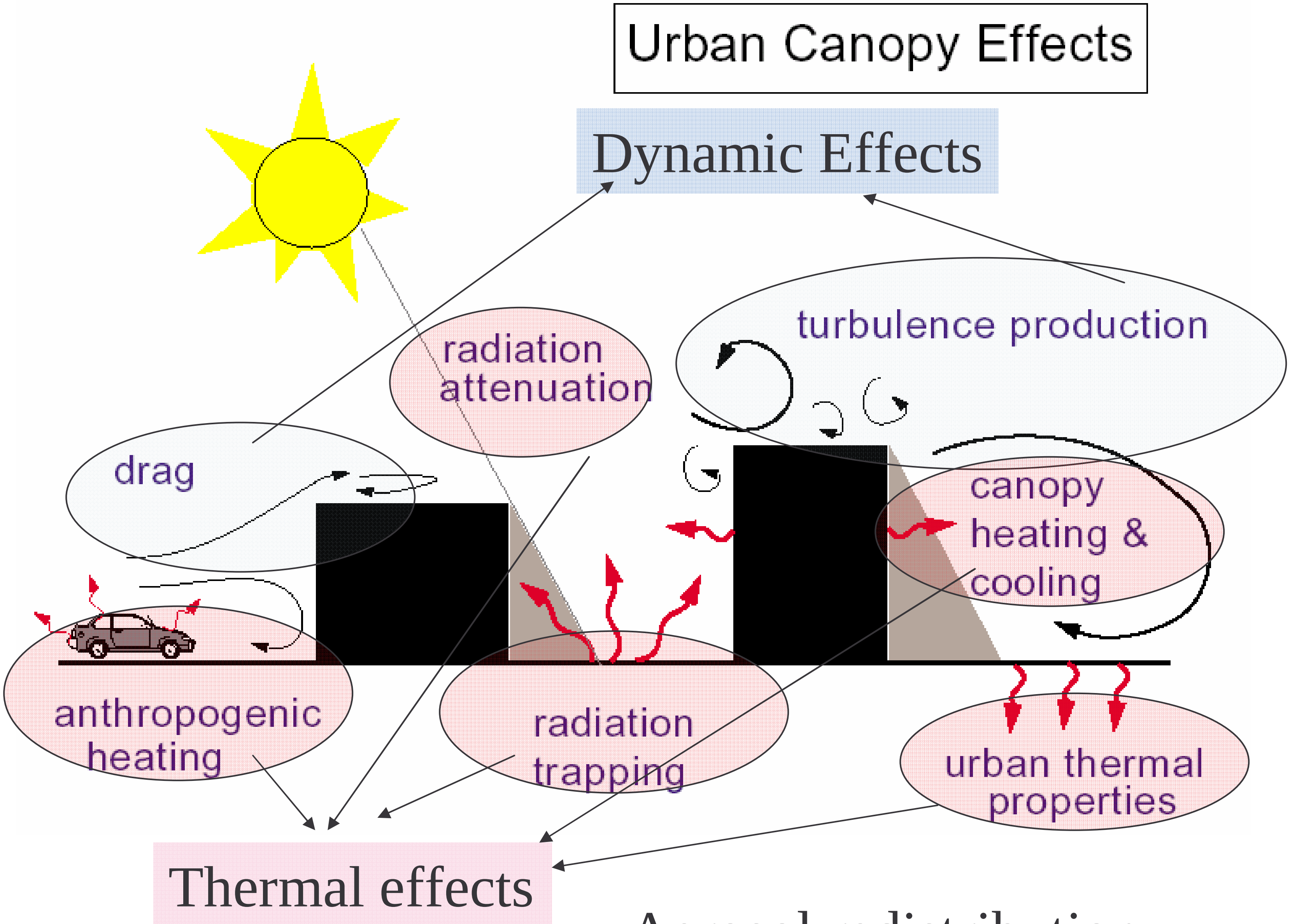
Computational Fluid Dynamic (CFD) models
Transport and Dispersion models
Chemistry models

Urban decision support systems

Urban Modeling Methods

- In-building scale modeling (typical grid < 1 meter; using Computational Fluid Dynamic (CFD) model; forecast time: seconds to minutes)
- Single to many building scale modeling (typical grid: 1-100 meter; using CFD model; forecast time: minutes to a few hours)
- **Urban-canopy model parameterization (> 100 meters; forecast time: many hours)**

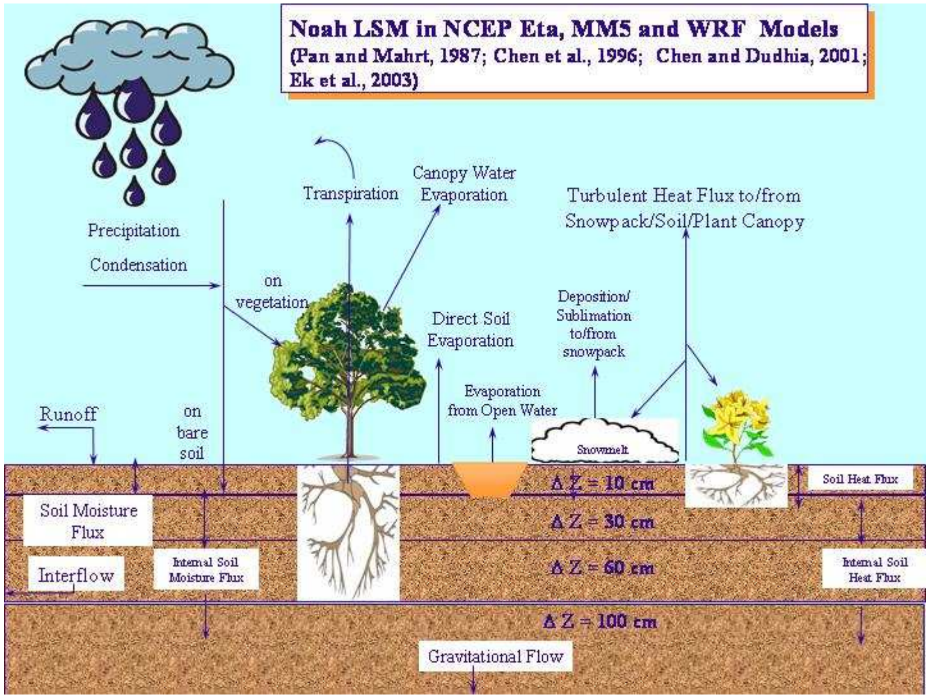




Aerosol redistribution

The Unified Noah LSM

- A land surface model primarily for NWP community, also for air pollution and regional hydrology applications
- Collaborative effort among NCEP, NCAR, AFWA, NASA, and universities
  - Annual WRF LSM working group meetings
  - Noah implemented/tested in operational NWP models at NCEP, NRL, and AFWA
  - Noah was implemented in the pristine WRF V2.0 (May 2004)



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Urban Modeling Methods in the Unified Noah Land Surface Model

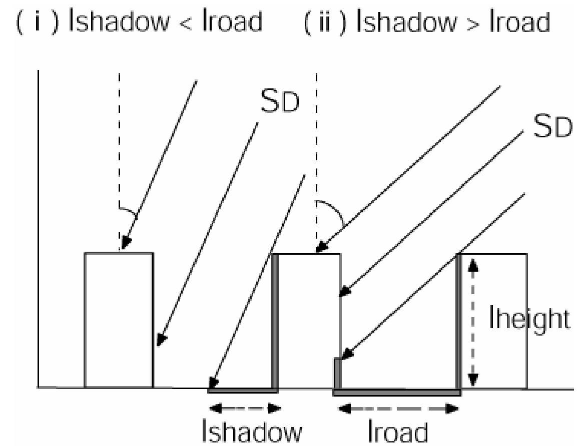
- Degree of complexity of urban modeling
- We developed two methods for urban land-use modeling
  - Simple bulk parameterization of urban effects in MM5/Noah
  - Complex Urban-Canopy Model coupled to WRF/Noah
- These urban models in MM5/WRF were applied for
  - Oklahoma City
  - Phoenix
  - Houston
  - Salt Lake City
  - Hong Kong
  - Beijing
  - Tokyo

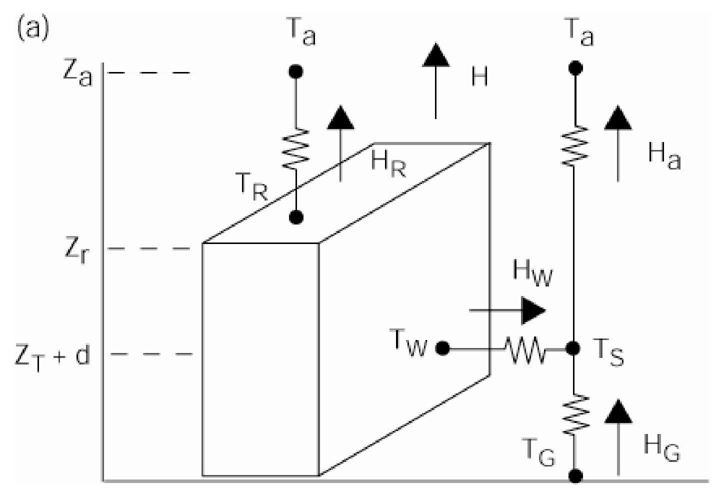
Simple Parameterization of Urban Effects in the Noah LSM

- Large roughness length
  - turbulence generated by roughness elements
  - drag due to buildings
- Small albedo
  - radiation trapping
- Large thermal capacity and thermal conductivity
  - heat storage in soil
- Low evaporation
- Implemented in MM5 V3.7 and WRF V2.0

WRF/Noah LSM/Urban-Canopy Coupled Model

- Single layer urban-canopy model (UCM, based on Kusaka 2001)
  - 2-D urban geometry (orientation, diurnal cycle of solar azimuth)
  - Street canyons with sky view factor
  - Shadowing from buildings and reflection of radiation
  - Anthropogenic heating
  - Multi-layer roof, wall and road models





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Role of Vegetation and Canopy Resistance

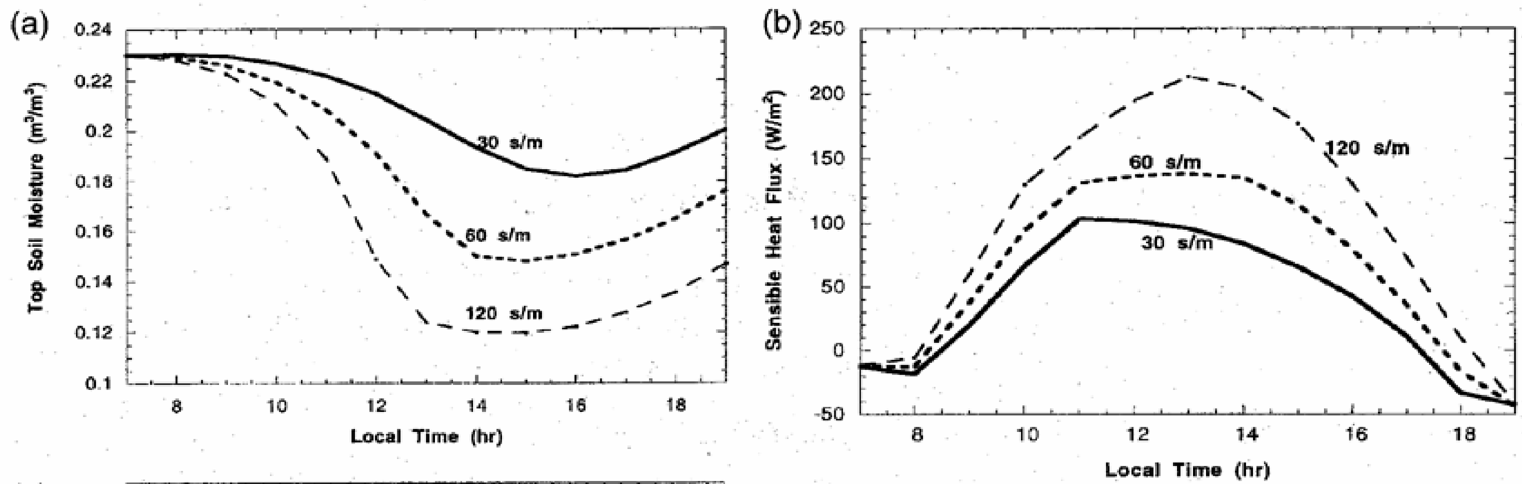
- Urban canopy model is coupled to the Noah LSM
  - Use fraction of urban coverage
- Vegetation: dry and wet deposition
- Canopy resistance (Rc)
  - Photosynthesis and interaction with aerosol is a key link between biosphere and atmosphere (CO_2 fluxes, BVOC emission, and evaporation, ozone effects)
  - Large uncertain in Rc
- Recent model experiments at NCEP highlight the emerging need to address the uncertainty of Rc in Noah

Current Jarvis-type Canopy Resistance (Rc) Scheme in Noah

- $Rc = Rc_{min} / f(\text{environment})$
- Rc significantly depends on Rc_{min} specified as function of land-use type
- Advantages:
  - Concept has evolved over time
  - Widely used in Air quality /NWP community
  - Results are easy to tune
- Disadvantages:
  - Poor scientific basis
  - Rc_{min} cannot be measured and is not constant (significant seasonal and intra-specie variability)

Effect of Change in Canopy Resistance on the simulated PBL structure

[Typically, Rs change by factor of 4 (from 30 to 120 s/m), altered energy fluxes by factor of 2!]



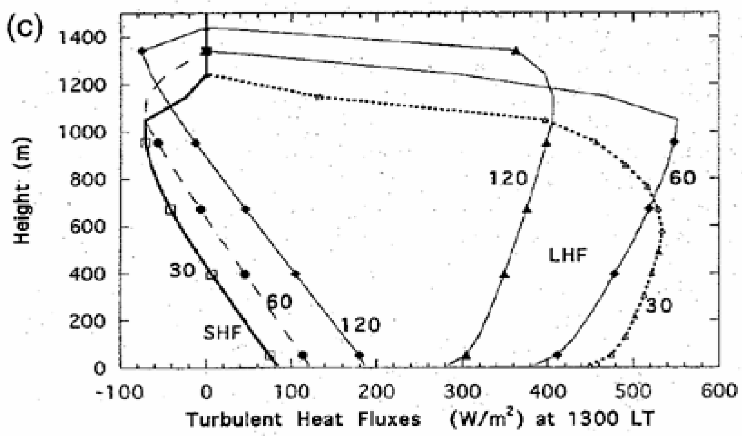
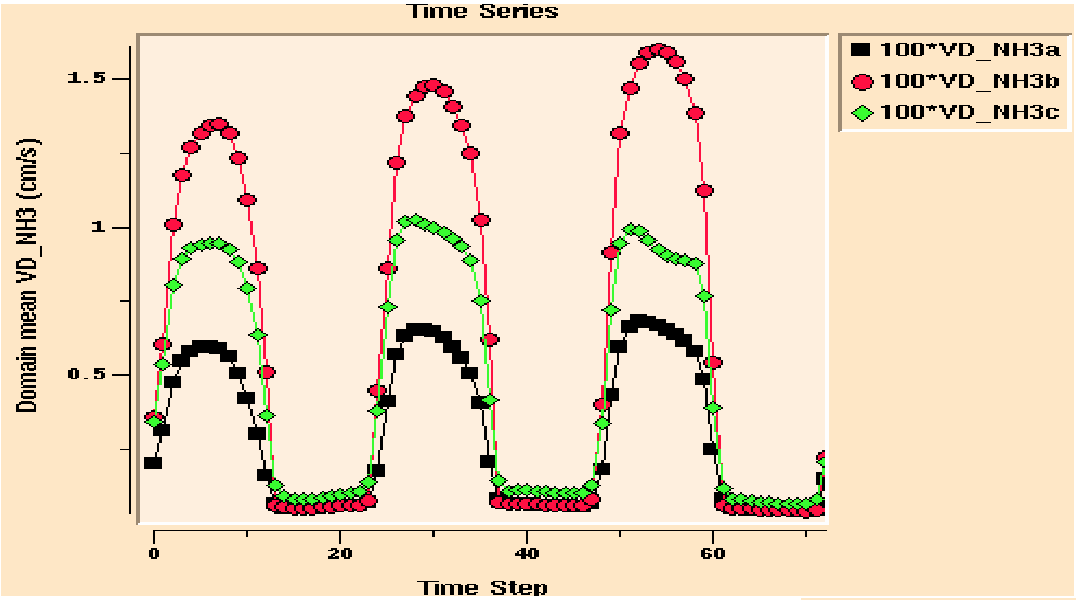


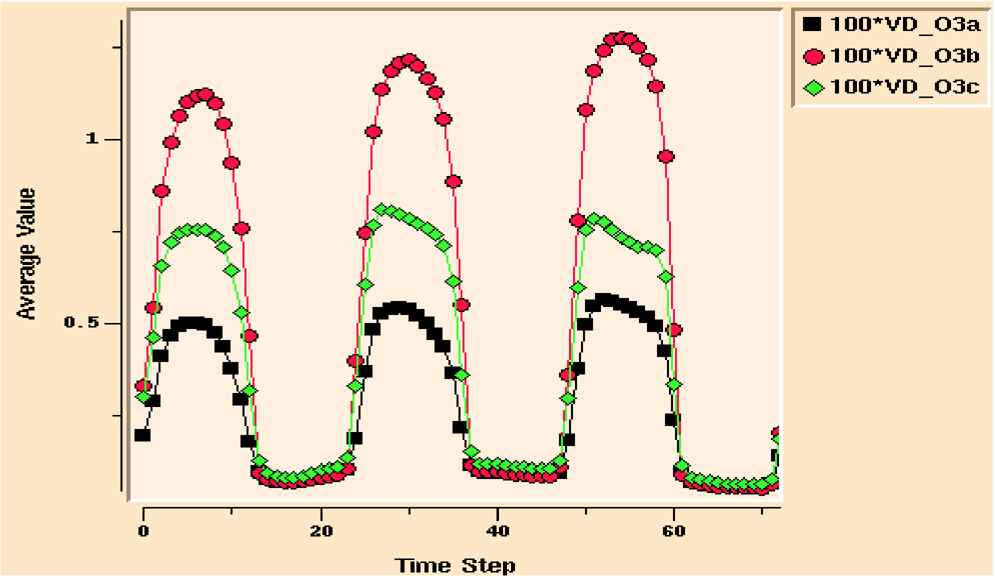
FIG. 1. (a) Resulting top soil moisture (10-cm-thick layer) variation for changes in the initial $R_{s\,min}$ values. In the figure, 30, 60, and 120 refer to the $R_{s\,min}$ values (s m^{-1}) considered. (b) Same as in (a) except for surface sensible heat flux. Notice the peak values for the extreme cases (30 and 120 s m^{-1}) differ by almost a factor of 2. (c) Same as in (a) except for turbulent heat flux profiles. Sensible heat fluxes are plotted on the left and are denoted by SHF, while the latent heat fluxes are on the right and are denoted by LHF.

CMAQ Results from Dev Niyogi (Purdue U)
Black (WESLEY); Red (Ball-Berry); Green (Jarvis)



Ammonia Deposition Velocities

Entire domain Average

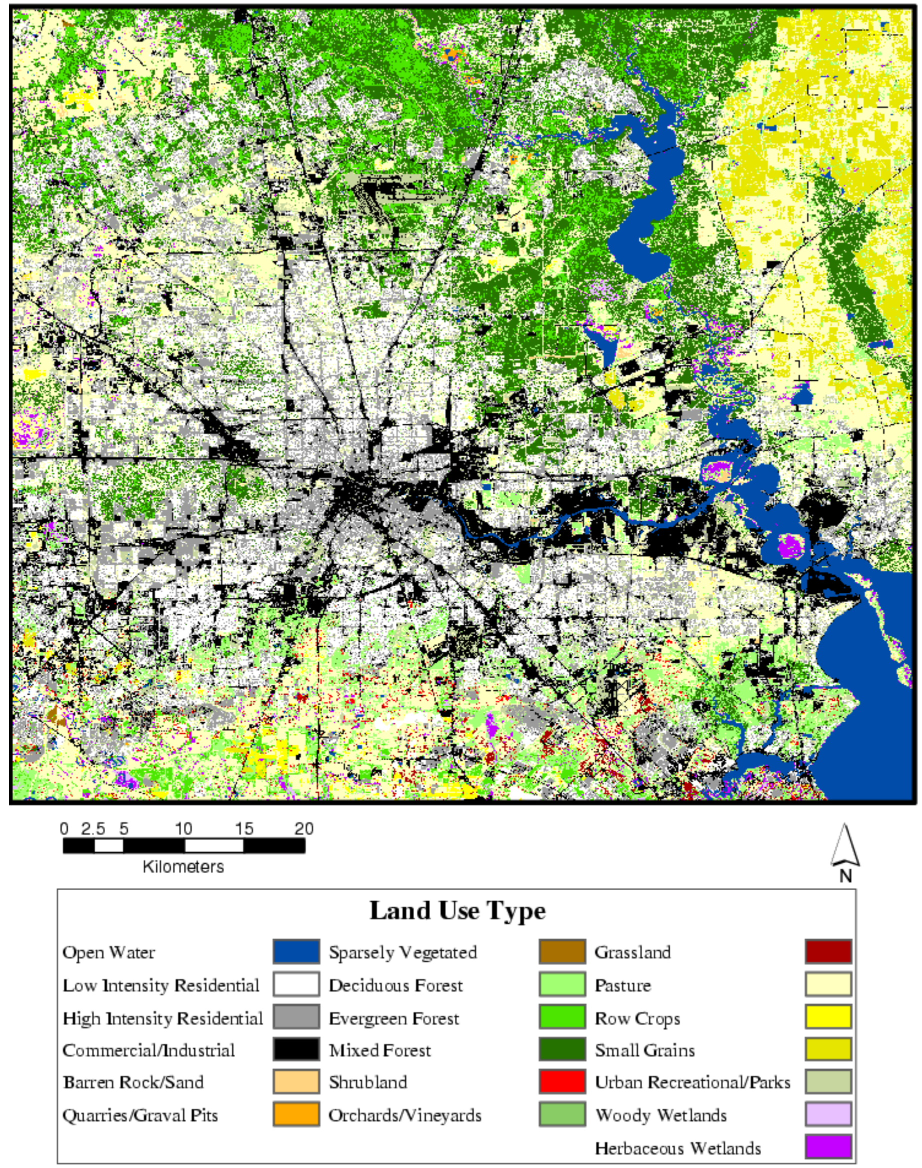


Average over NC

All underestimated
Ball-Berry is closer to observed value around 2

Integrate new remote-sensing data

ASTER - 15m
Beijing land-cover
April 9, 2004



30-m Landsat
land-cover Houston

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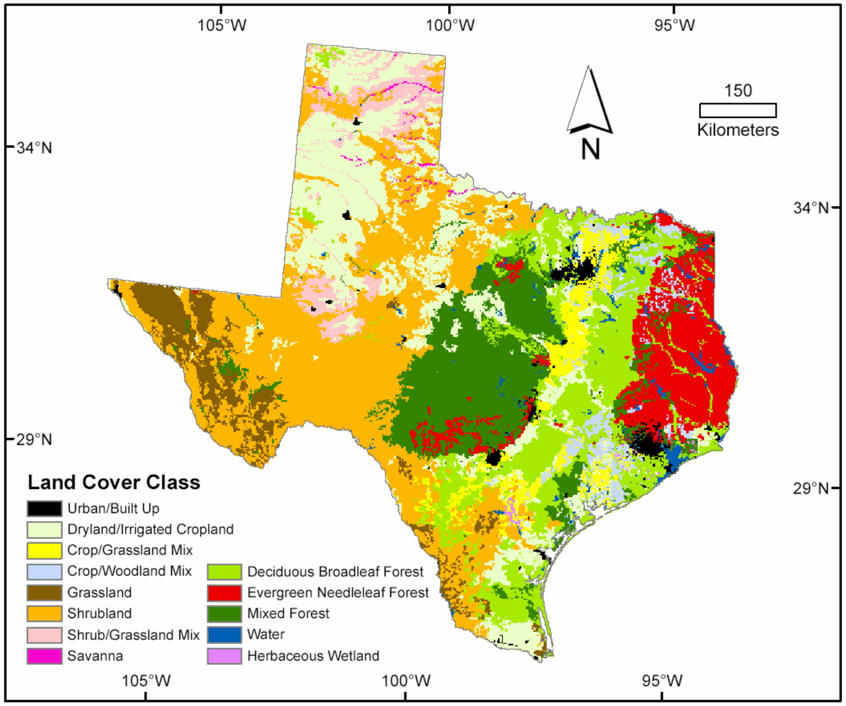
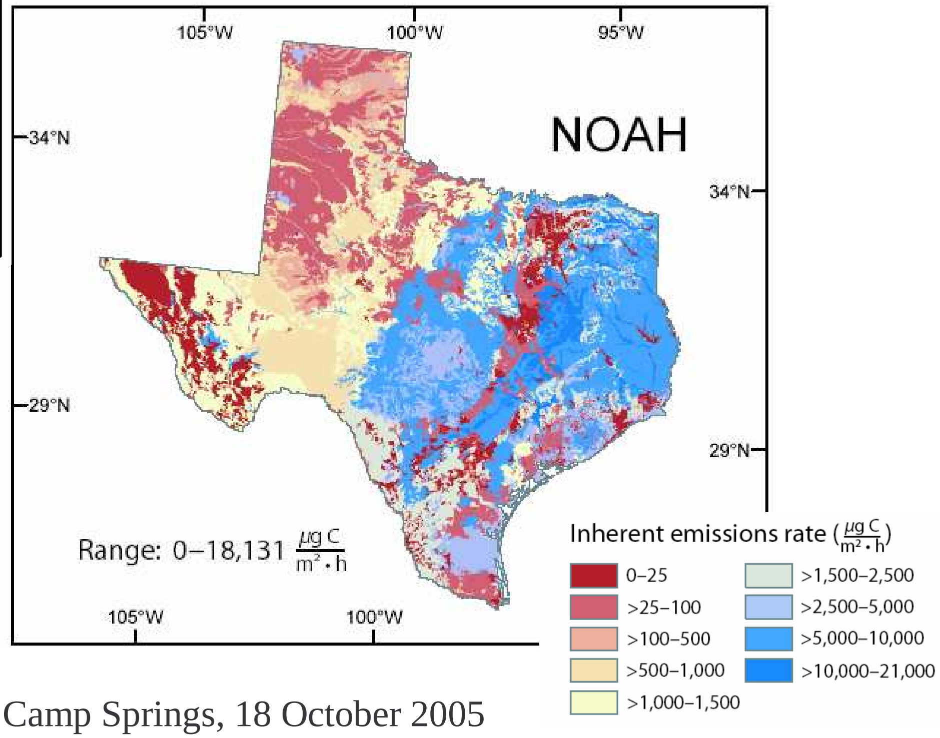
Integrate surface emission map



- BVOC (biogenic volatile organic compounds) type i (isoprene, monoterpene,)

$$F_i = \varepsilon_i \, D \, (L_{sun} + L_{shade})_i \, T_i$$

- BVOC emission and anthropogenic Nox, from Eastern TX form O3 over central TX



Surface biogenic emission calculated by the Noah LSM (Gulden and Yang, 2005, U Texas)

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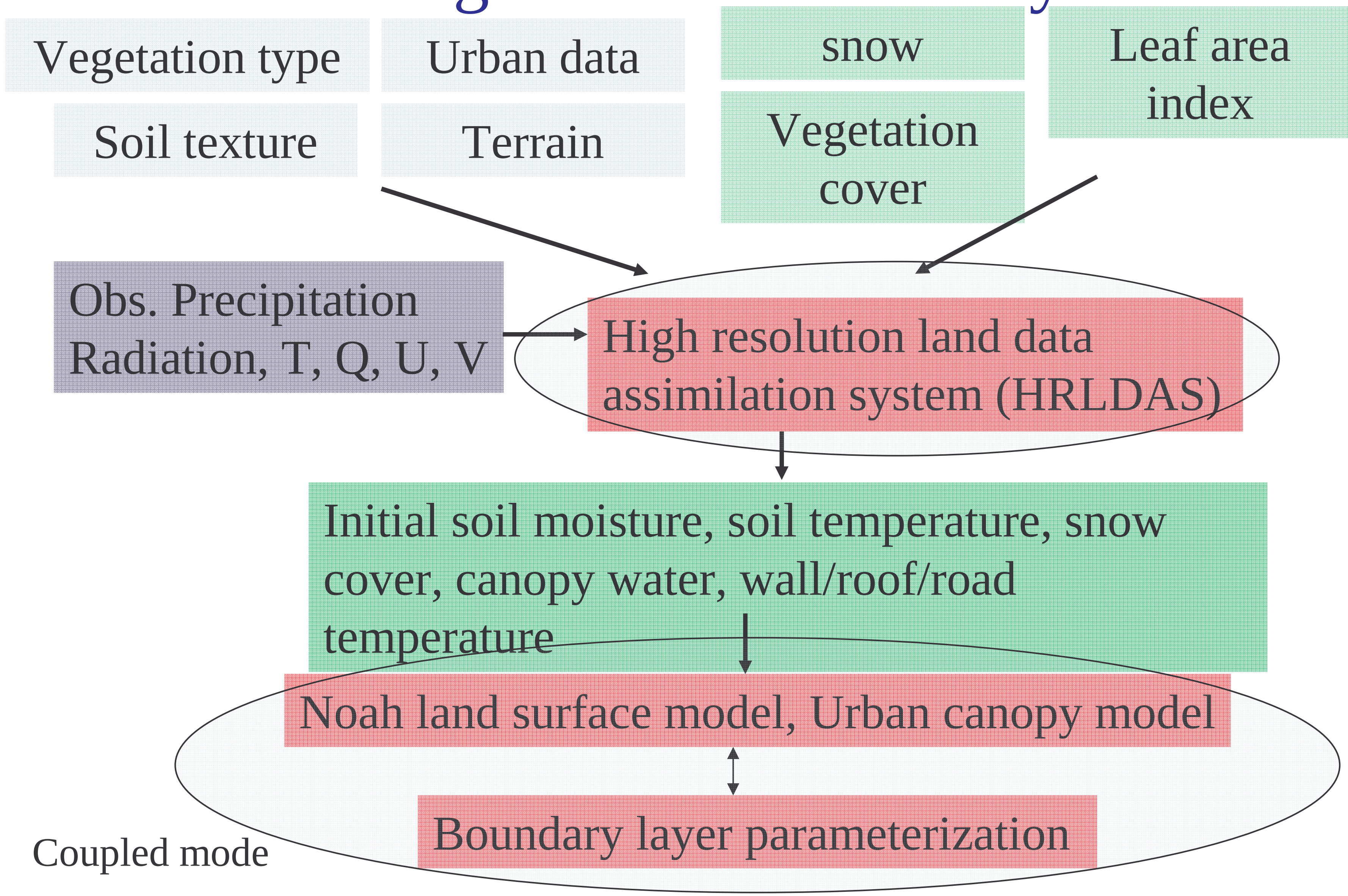
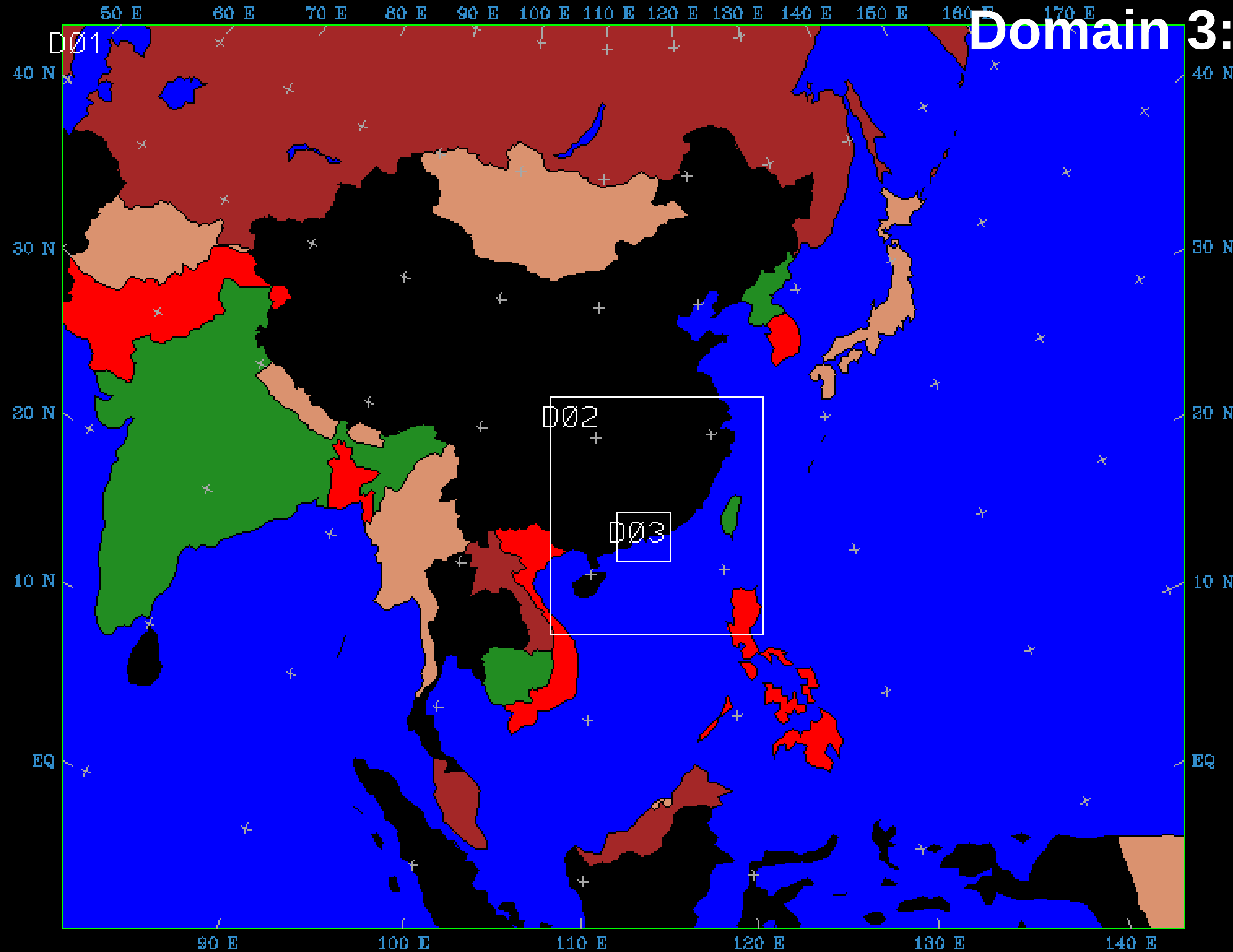
High-resolution land surface and urban modeling and assimilation system

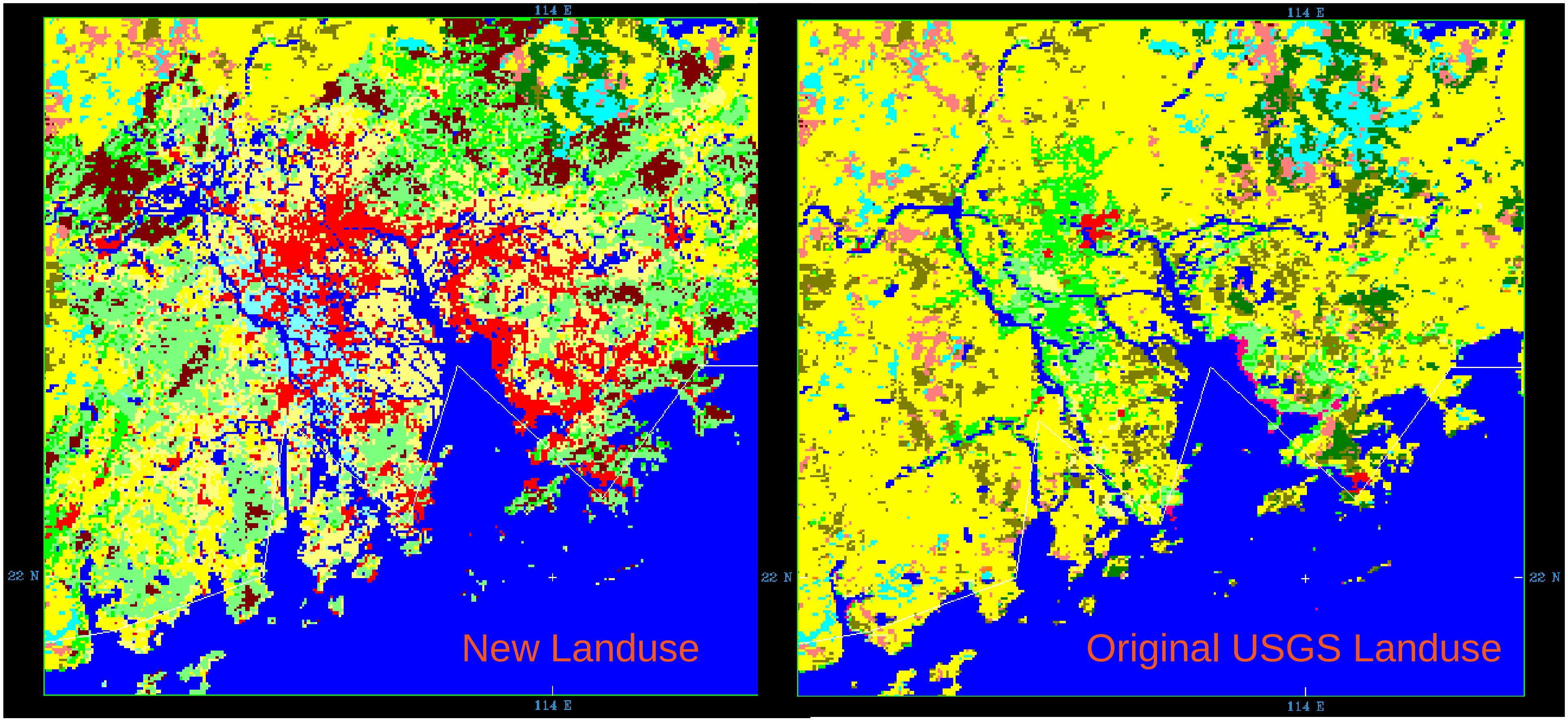


Domain 1: 40.5km

Domain 2: 13.5km

Domain 3: 4.5km

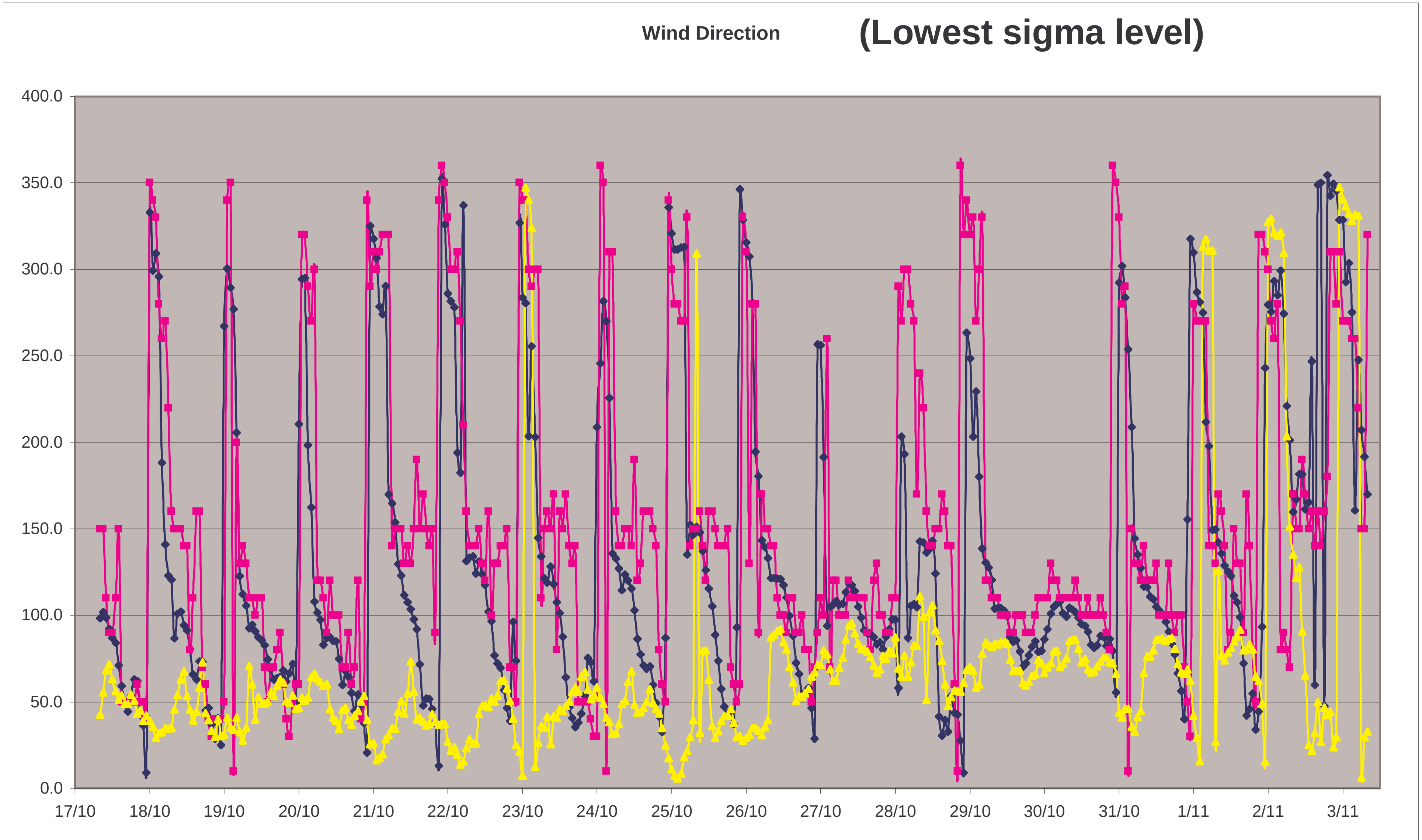




- §1km grid size for the Pearl River Delta area.
- §Much more urban areas
- §Better river network and water bodies

Urban	Evergrn. Broadlf.
Drylnd. Crop. Past.	Irrg. Crop. Past.
Shrubland	Crop./Grs. Mosaic
Wooded Wetland	Grassland

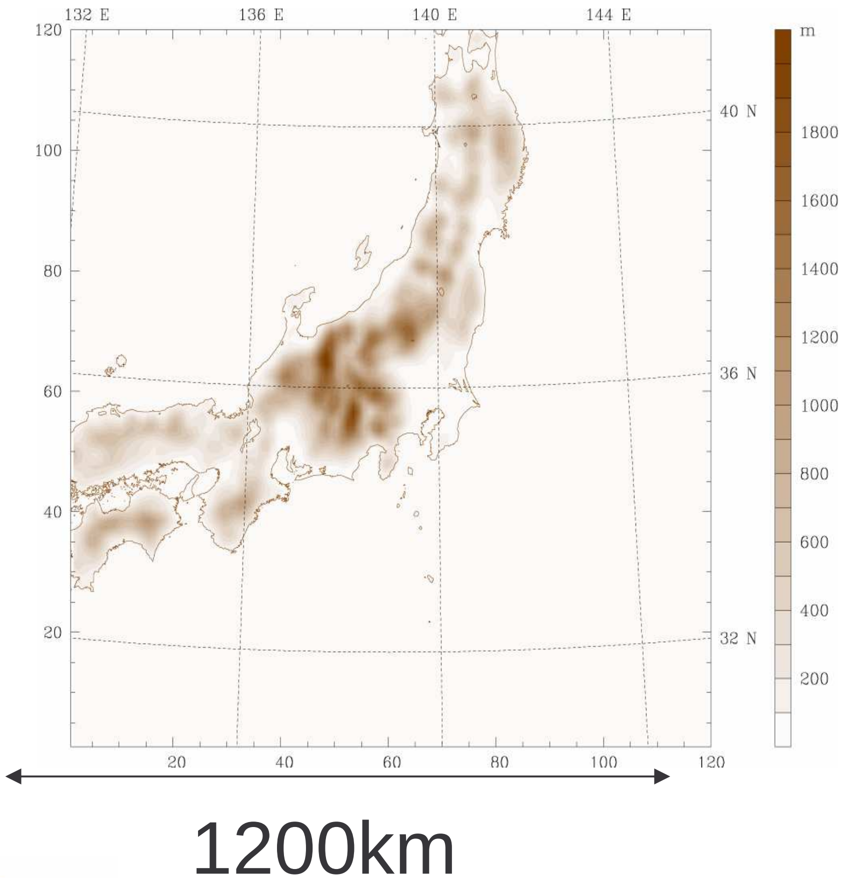
Main Land Use Categories (USGS based)

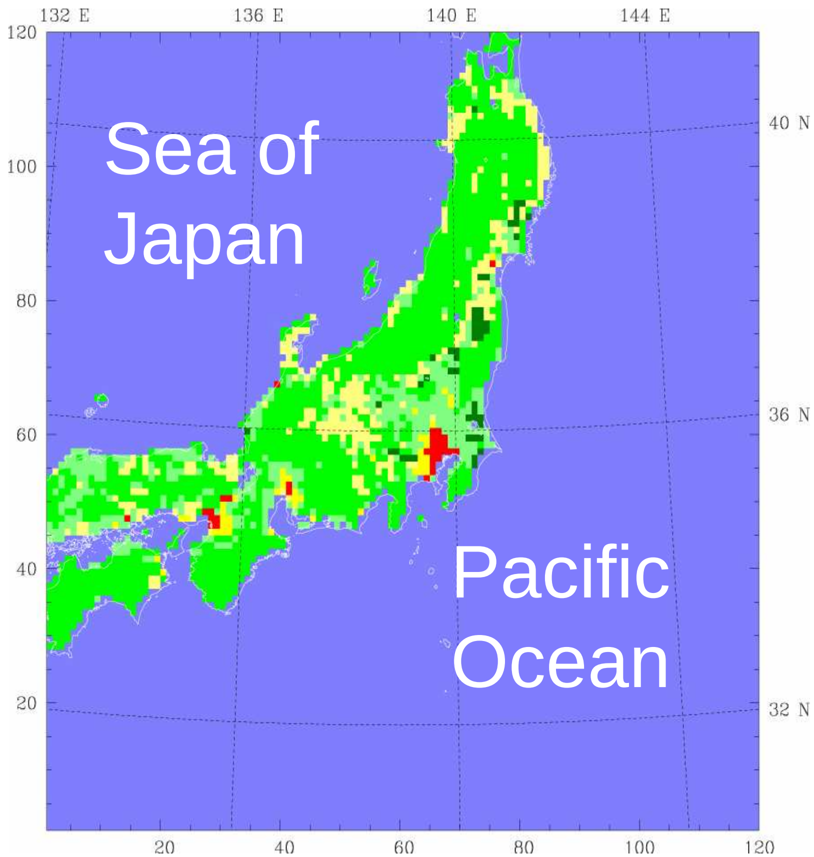


LSM (with urban modification) capture well the land sea breeze circulation enhanced by urban

Magenta :Observation
Blue: LSM forecast
Yellow: MM5 forecast

Terrain and Land-use of the Model Domain with 10-km grid spacing





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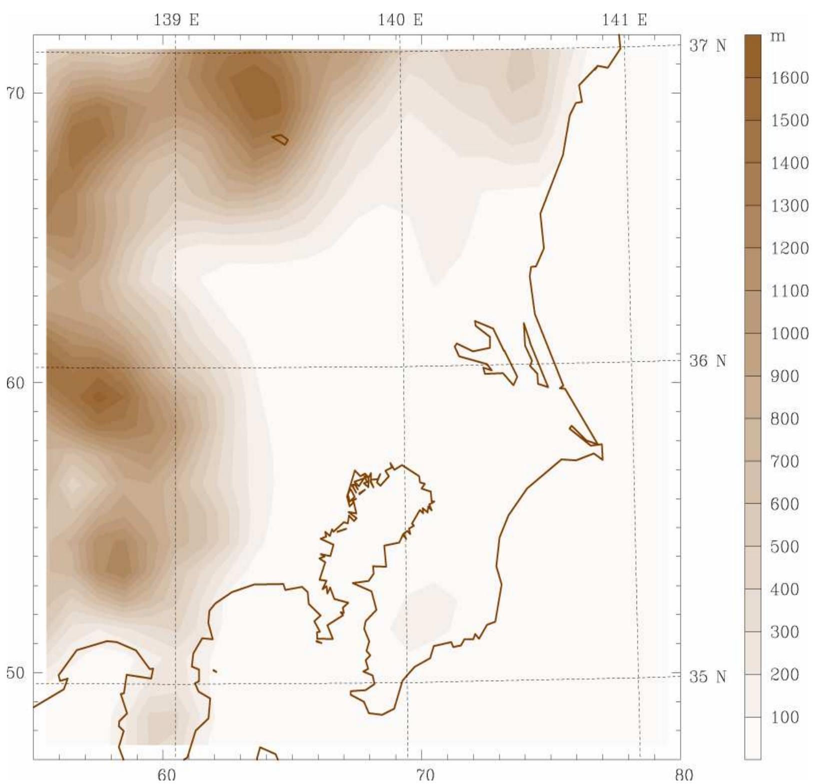
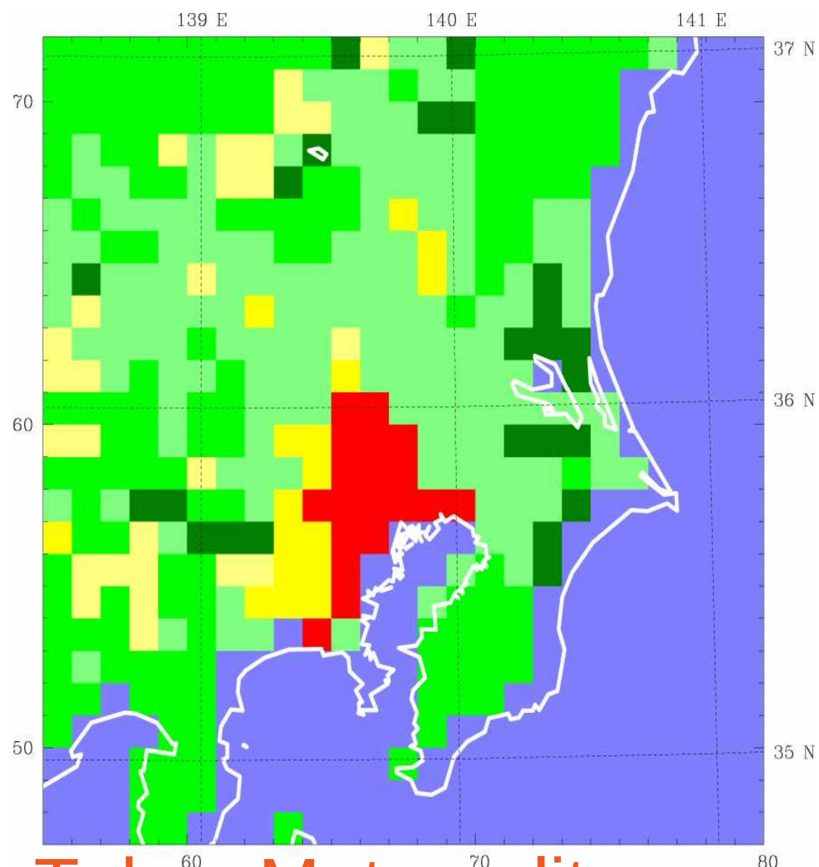
Terrain and Land-use around Tokyo





Tokyo Metropolitan area

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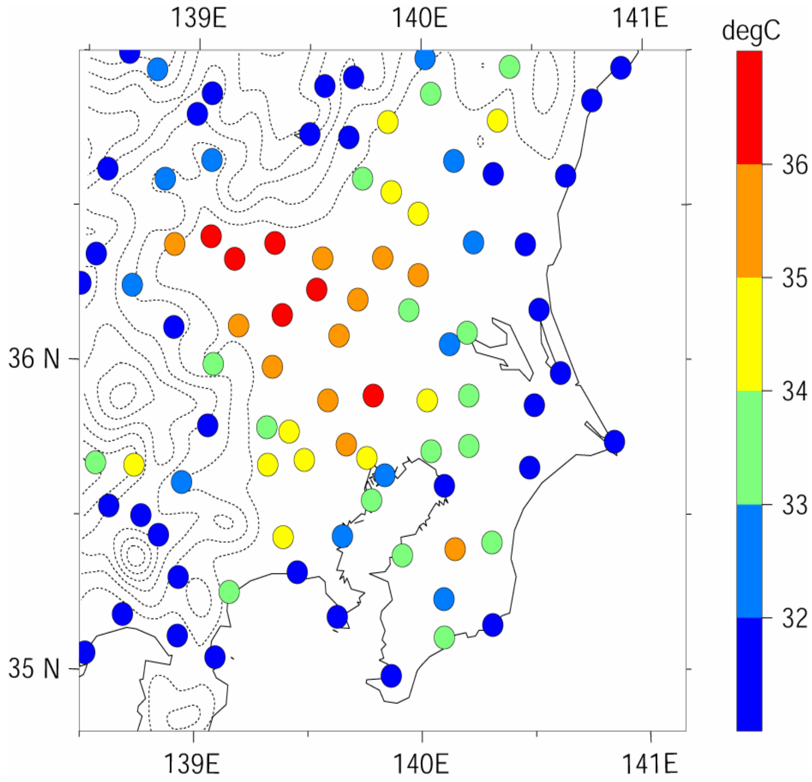
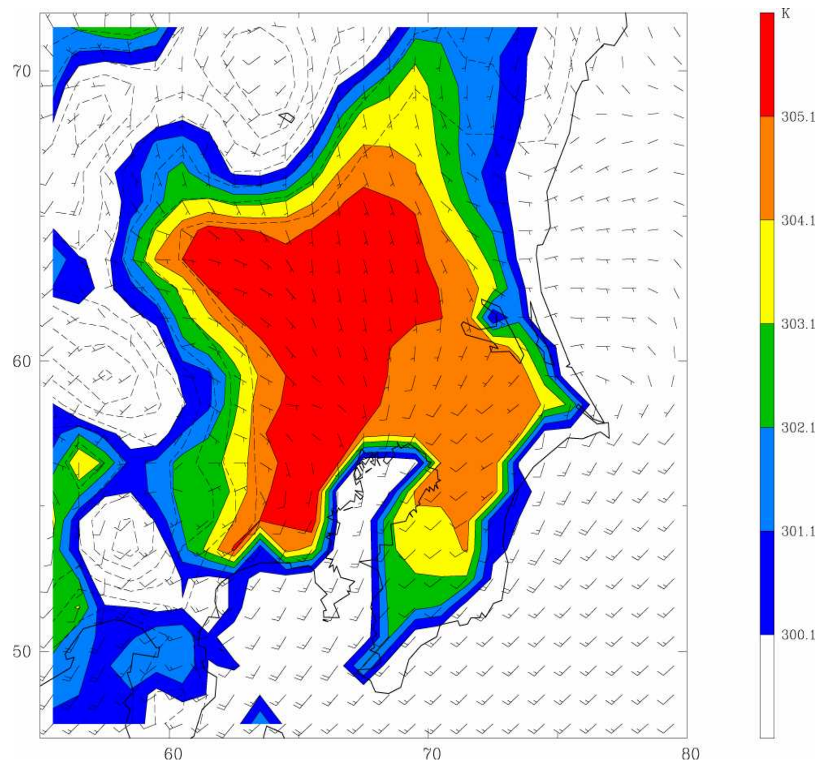
Daytime Urban Heat Island
2-m Temperature on 1500 LST

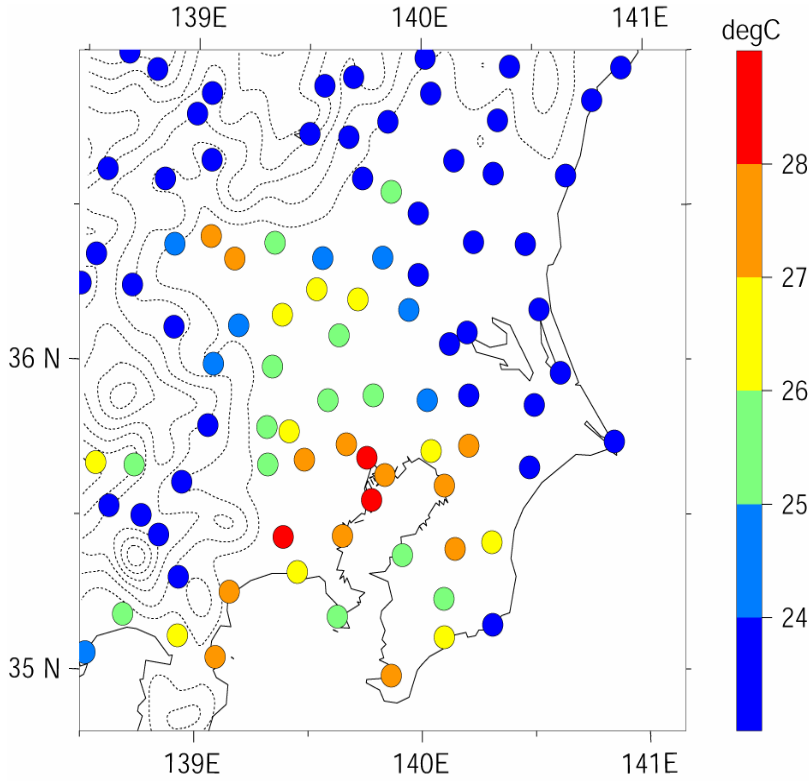
Obs WRF

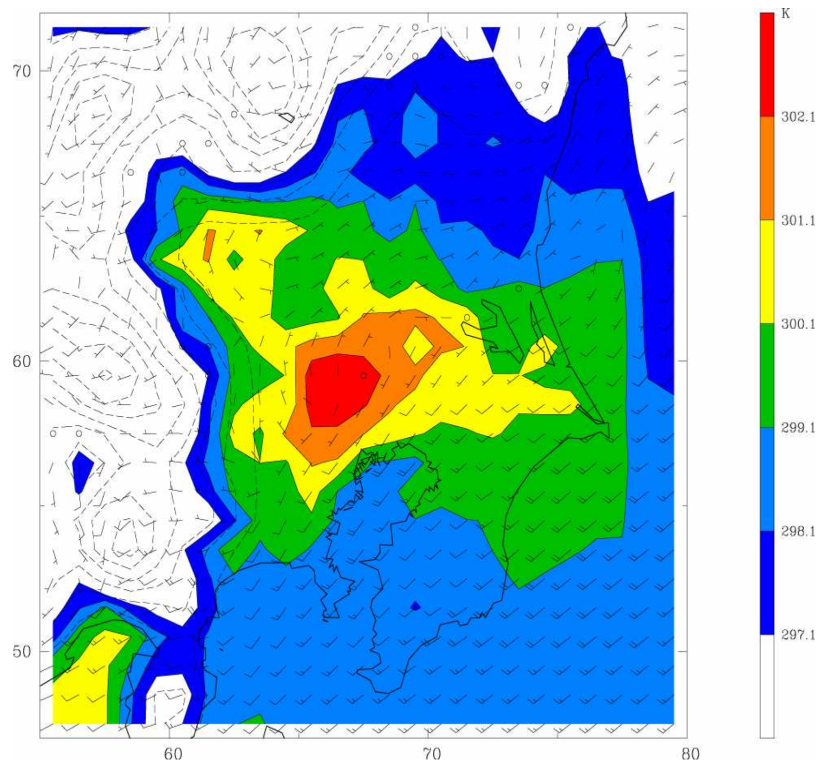




Nighttime Urban Heat Island
2-m Temperature at 0300 LST

Obs WRF





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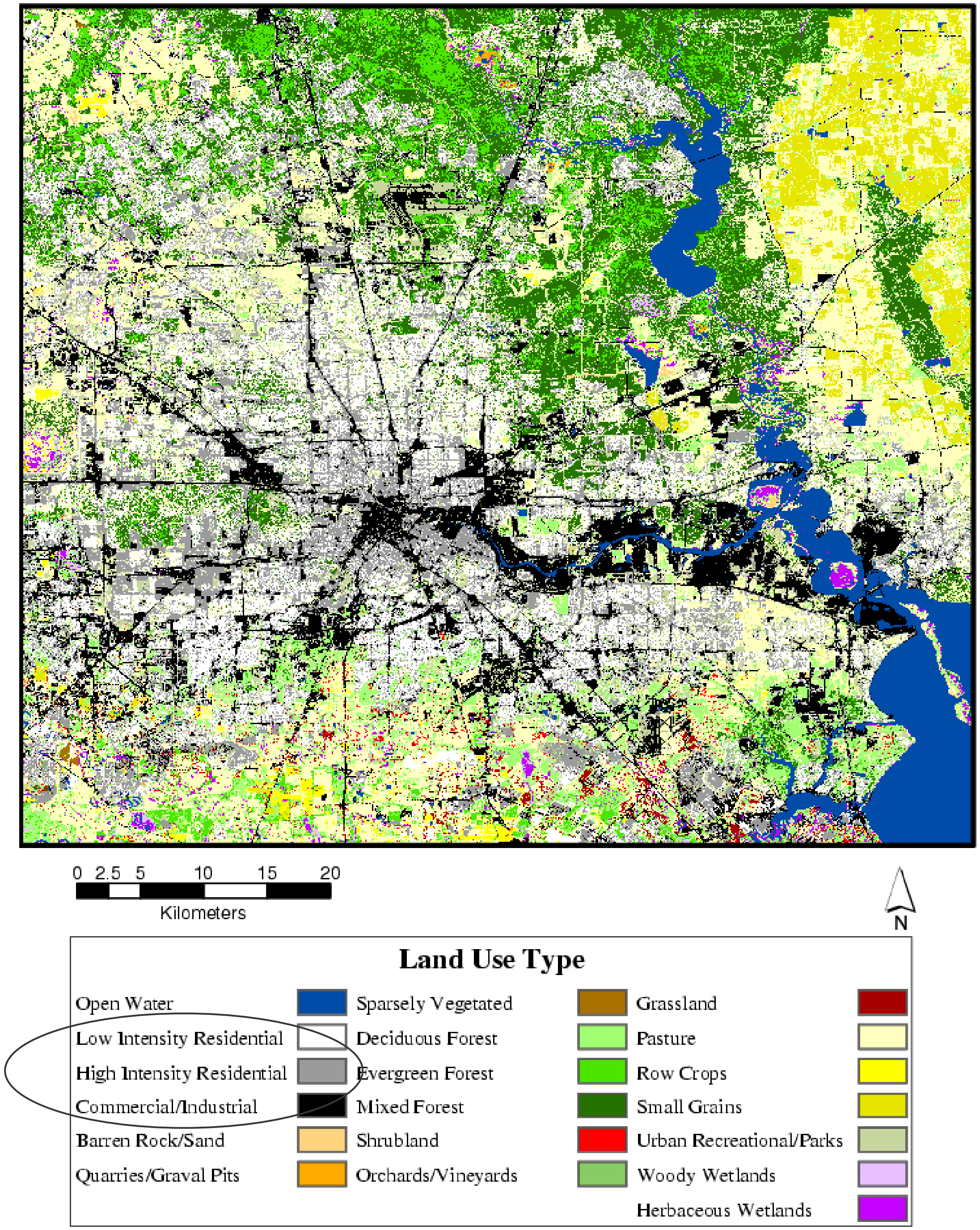

Landsat
30-meter resolution
Landuse for the
Houston Area

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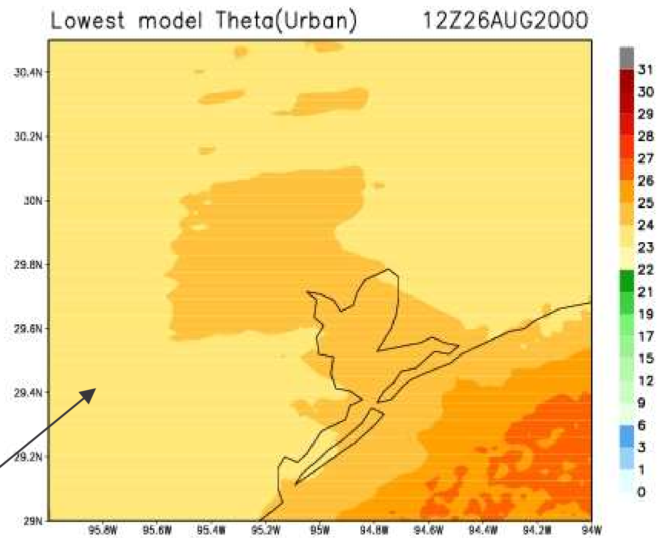
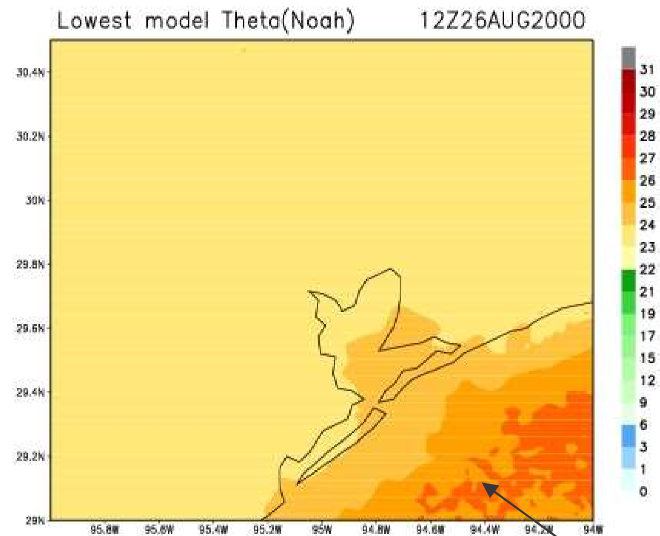
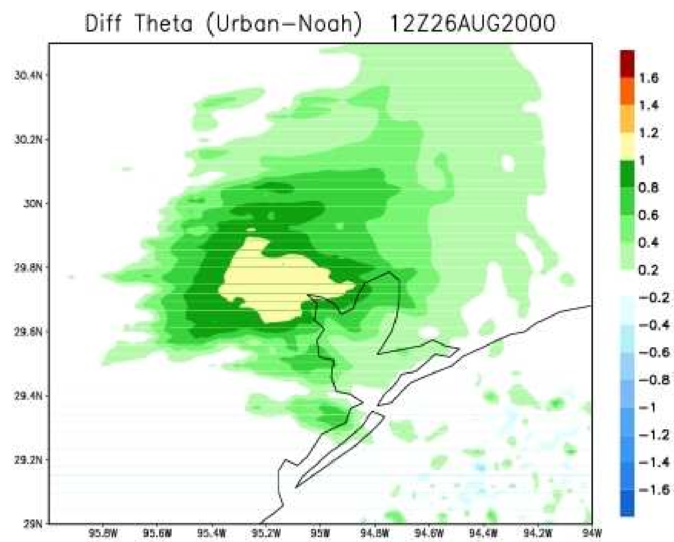
UCM Produce More Pronounced Nocturnal Heat Island

Lowest model level at 12 UTC 26 Aug 2000 (1-km WRF)





With Urban Canopy Model
and new urban landuse



Simple urban treatment

Old urban landuse map

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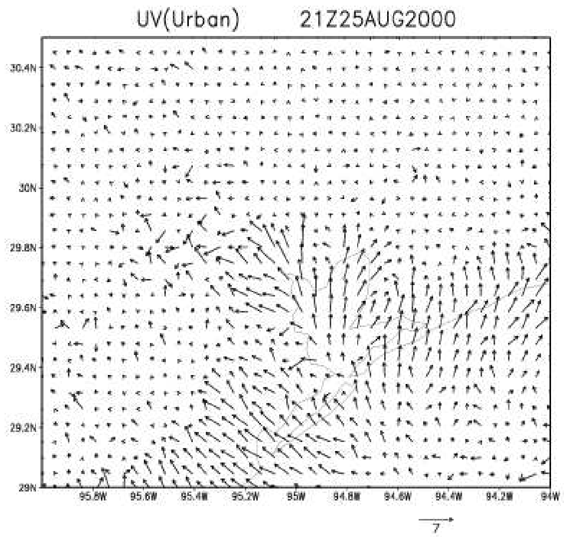
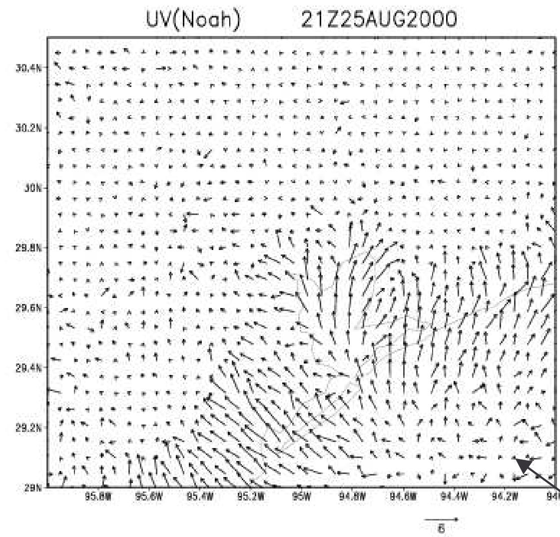
Enhanced Strength of Sea Breeze by UCM

lowest-model level wind field at 21 UTC 25 Aug 2000





With Urban Canopy Model
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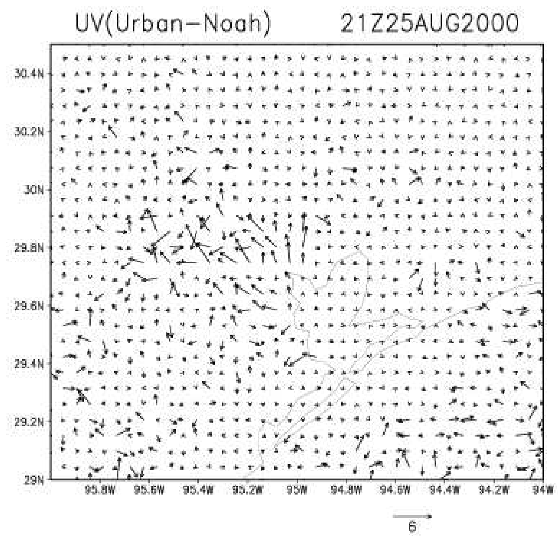

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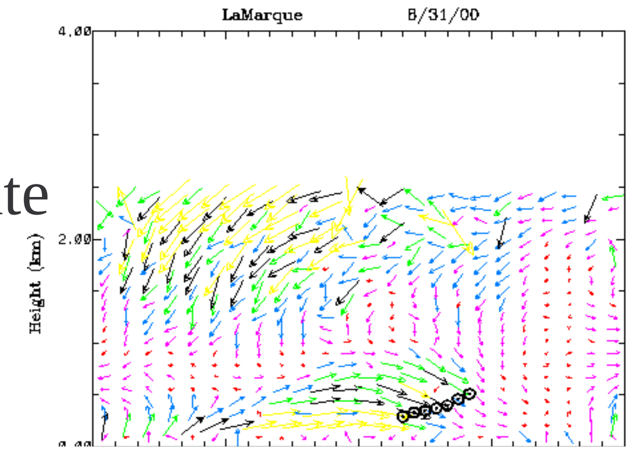
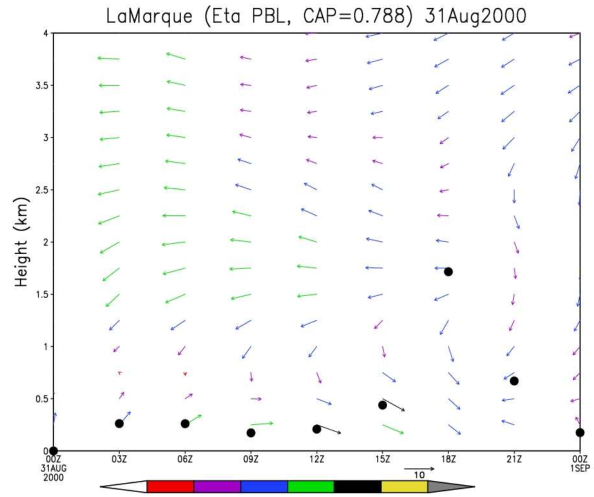
Diurnal Cycle of Wind Profile and PBL Depth
31 Aug 2000 @ LaMarque (near coast) and Houston

Hourly observation

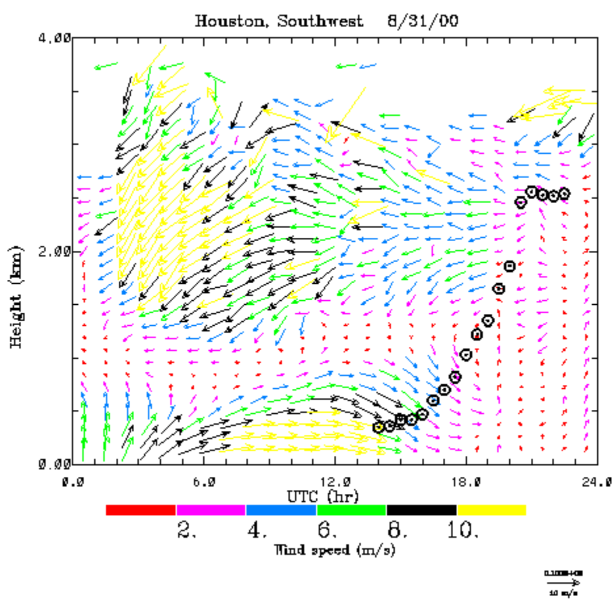
3-hr WRF 1-km simulation

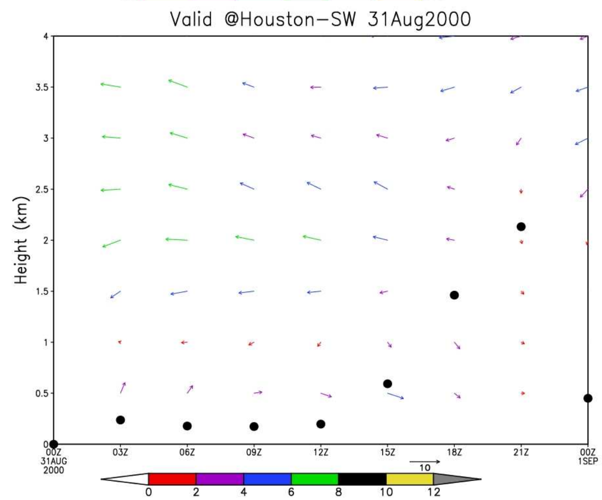
LaMarque site





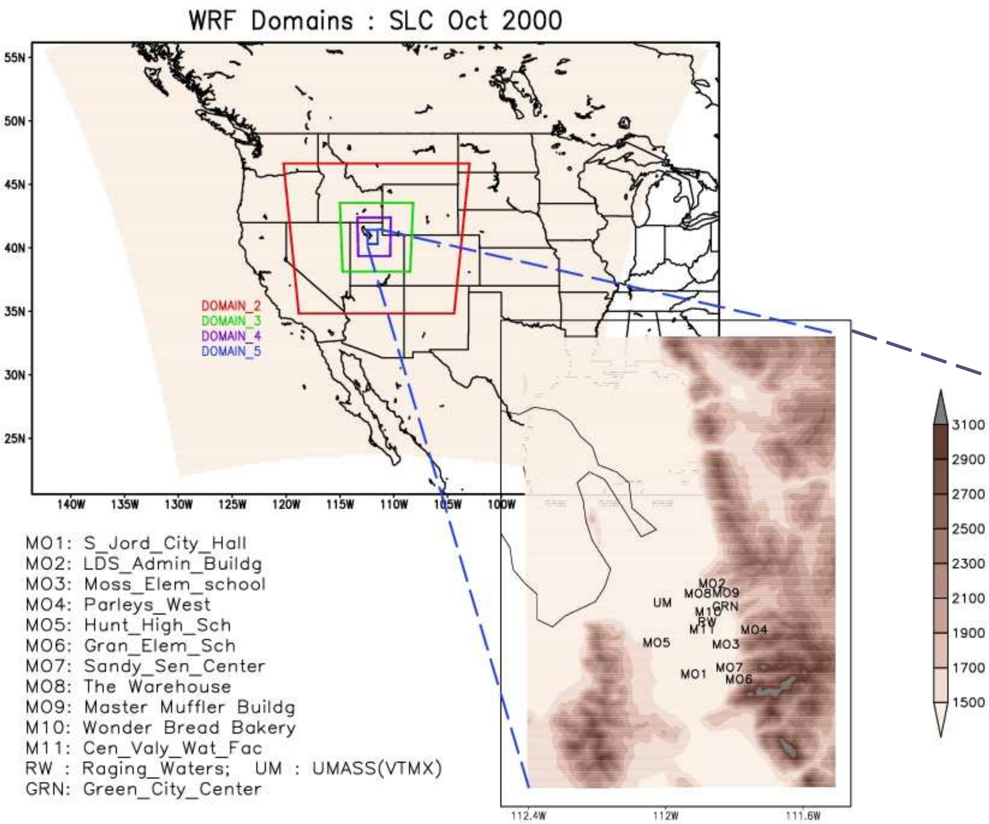
Southwest Houston site





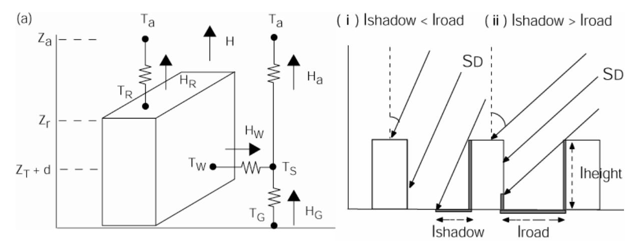
High-Resolution WRF/Noah/Urban Modeling Capability

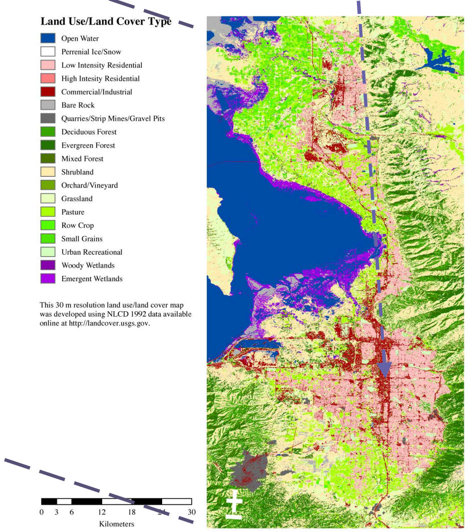
Domains: 40.5,13.5,4.5,1.5,0.5 km



Complex terrain on WRF nested D-5 (0.5 km grid spacing) over the Salt Lake City area

Single layer Urban Canopy Model

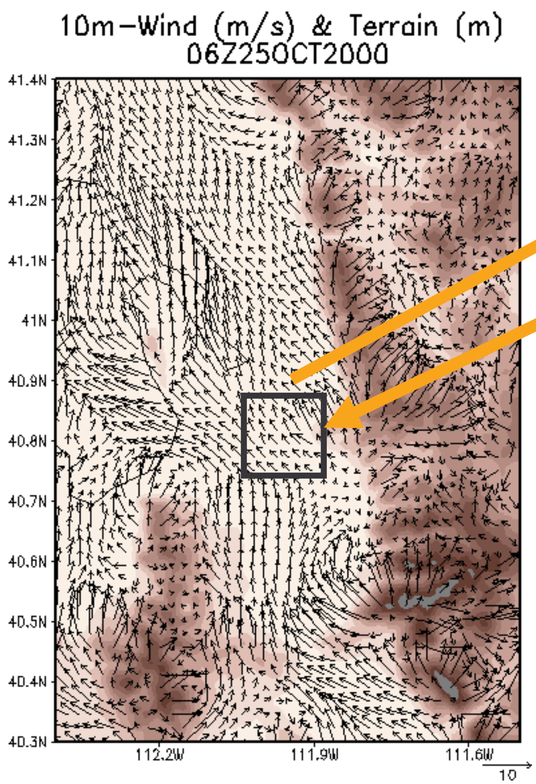




Complex Urban land use distribution over SLC

High-Resolution WRF/Noah/Urban Modeling Capability: Coupled to CFD-Urban

WRF-Noah/UCM coupled model forecast

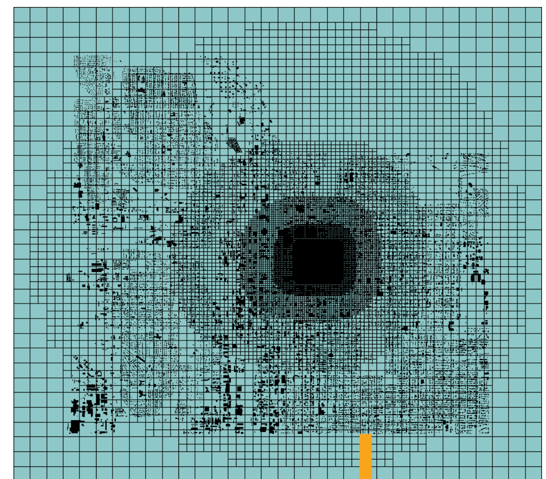


Coupling

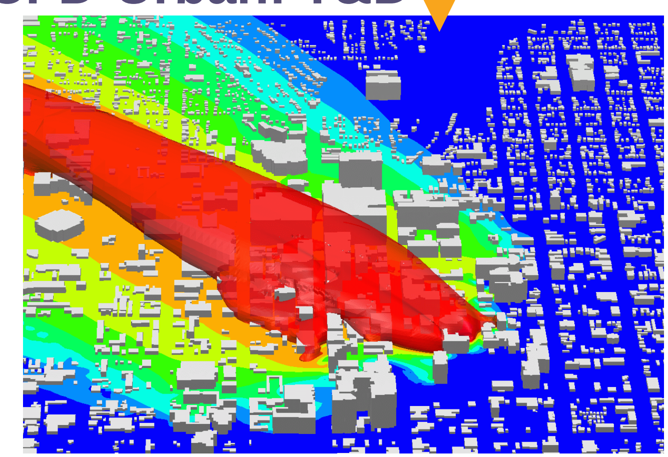
Down-Scale

Up-Scale

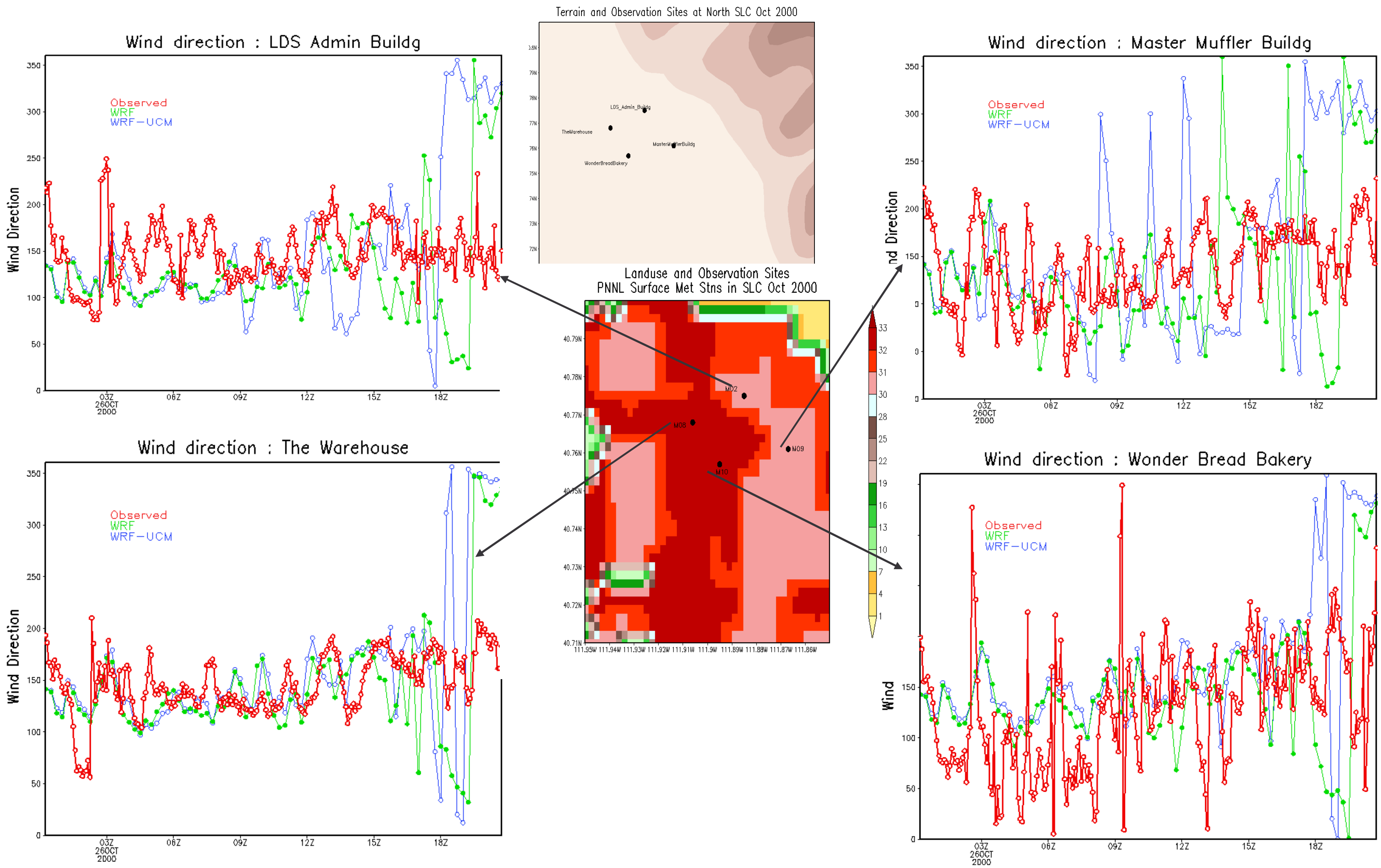
CFD-Urban: Hi-Res Urban Model



CFD-Urban: T&D



Diurnal Wind Direction in Northern Downtown

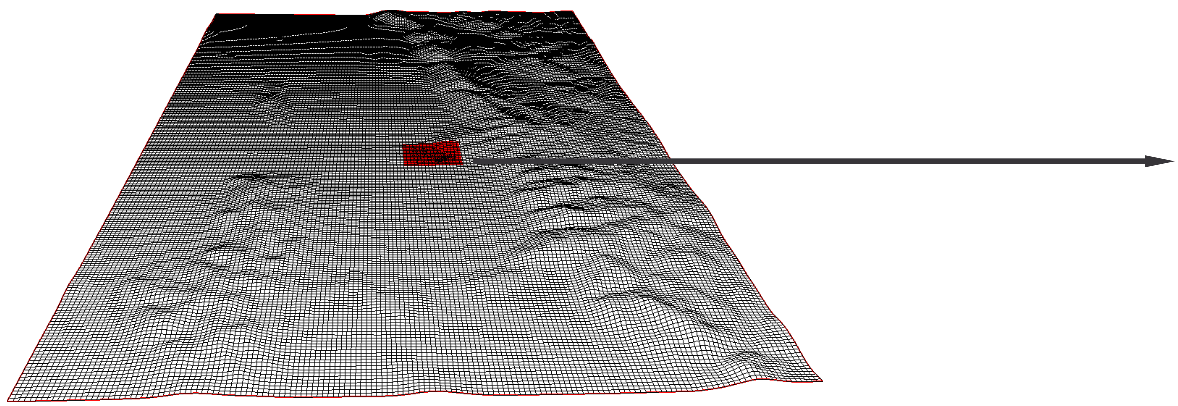


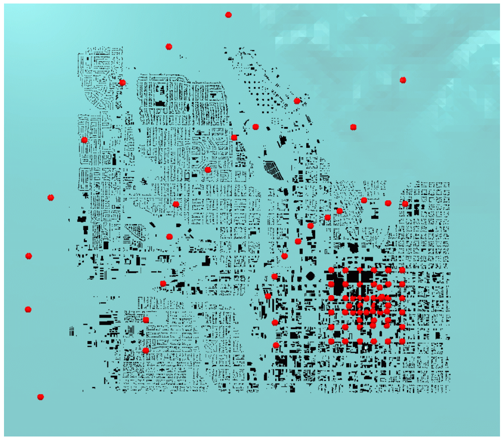
Red: Obs, Green: WRF/Noah,
Blue: WRF/Noah/UCM

NIGHT DAY

WRF/UCM - CFD Transport and Dispersion Preliminary Results: Urban IOP 10 Urban 2000

- Urban 2000: Field Test conducted in Salt Lake City
    - SF6 released in Central Business District (CBD)
    - Samplers located in CBD and on “arcs” located downstream
- Statistical Comparison of Predicted to Measured Concentration Data

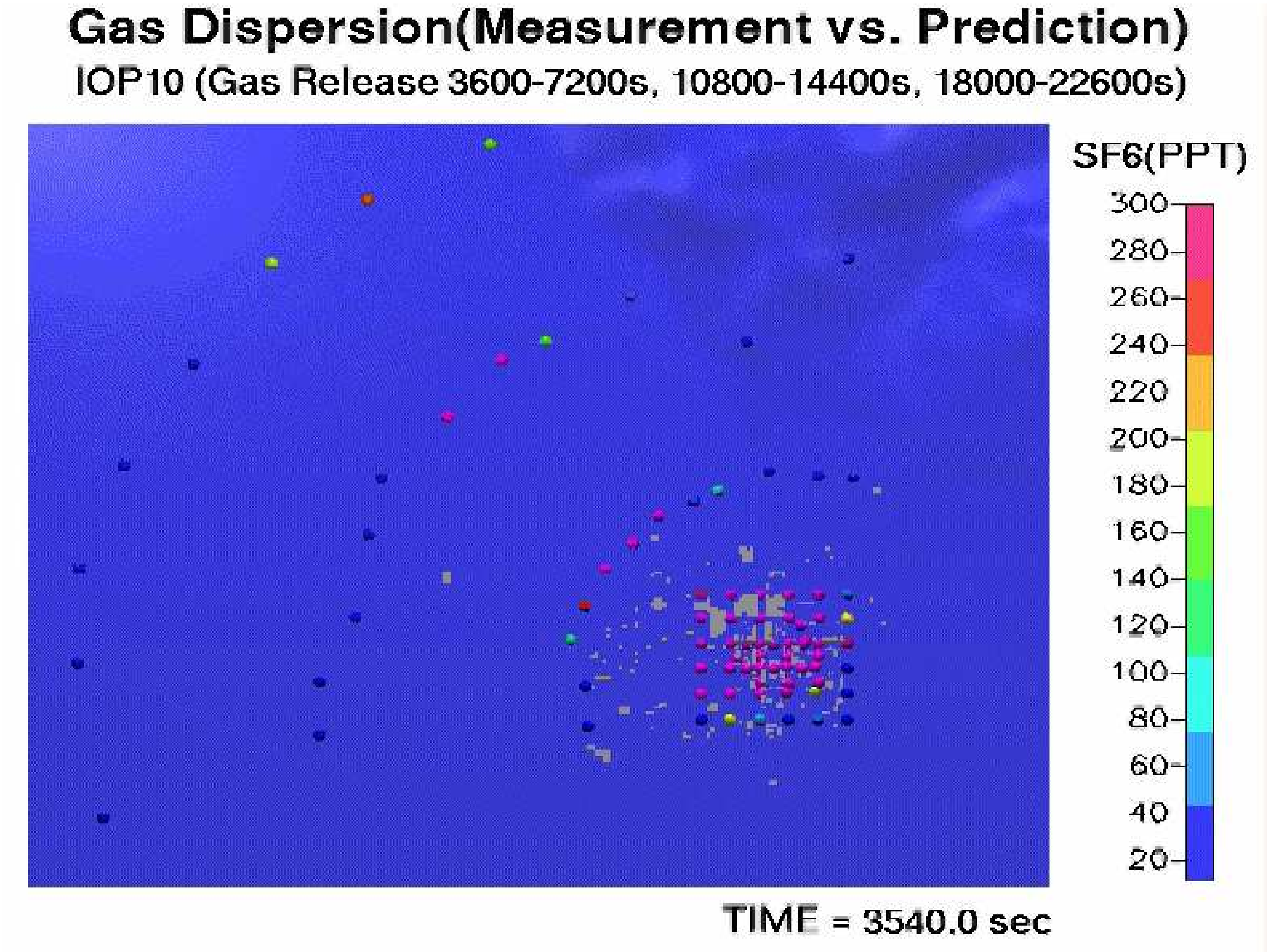




Courtesy of Bill Coirier, CFD Research Corporation

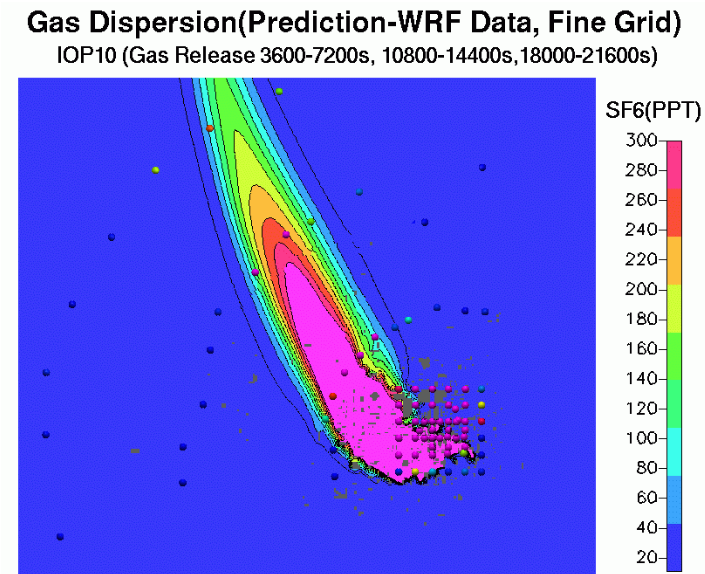
WRF/UCM - CFD Transport and Dispersion
Preliminary Results: Urban IOP 10 Urban 2000

- **Entire IOP 10**
  - **3 Releases/Pauses**
- **WRF Data for BC**
- **Quasi-steady approach:**
  - **Wind/Turbulence fields at 15 minute intervals**
  - **Unsteady T&D using Unified Frozen Hydro Solver**
- **Flow turning is replicated, which causes plume to travel NNW**

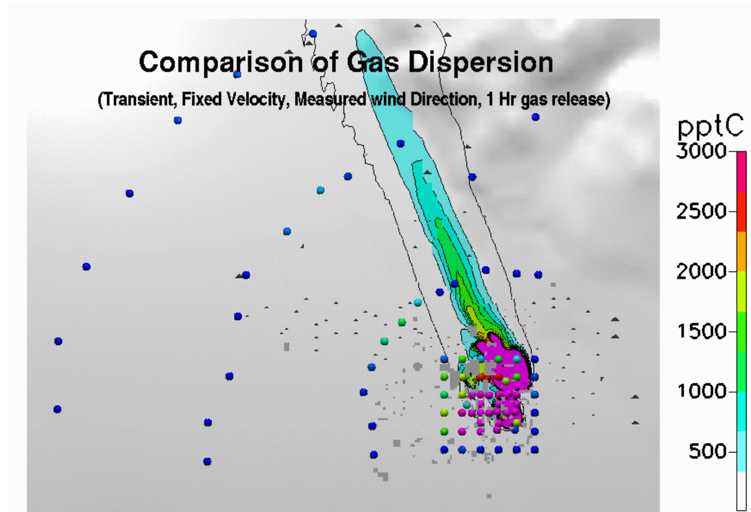


Courtesy of Bill Coirier, CFD Research Corporation

Gas Dispersion Prediction



	Near Source	R2	R3	R4	All
FB	-1.35	-0.2	0.1	0.9	-1.34
NMSE	147.98	0.65	0.6	2.6	232
MG	0.53	1.6	1.9	2.4	0.8
FAC2	0.51	0.42	0.6	0.4	0.5



	Near Source	R2	R3	R4	All
FB	0.85	1.59	1.44	1.7	0.87
NMSE	14.03	15.8	14.4	26.1	21.9
MG	25.42	14.1	4.58	5.06	15.8
FAC2	0.12	0.17	0.36	0.38	0.18

Using WRF 12-h forecast (left panel) significantly improve FAC2 (FAC>0.5 acceptable) and MG (0.7<MG<1.3 acceptable) over using single sounding approach (right panel)

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Summary

- Urban environmental problems can be addressed with an integrated mesoscale urban modeling system that should include
  - Urban canopy models
  - Remote sensing/in situ data at urban scales
    - urban geomorphologic data base for urban modeling (EPA, Jason Ching)
    - remote-sensing urban land-use data (NSF/NASA, Joe Zehnder at ASU)
  - Downscaling/upscaling with explicit CFD-type models
    - CFD model coupling (DTRA, Bill Coirier, CFDRC)
  - Integration into decision support systems
  - Surface biogenic and anthropogenic emission maps
  - Companion land data assimilation system

Summary

- A consistent canopy resistance treatment in Noah is critical for both NWP and air pollution applications
  - Plan to systematically evaluate different types of Rc schemes in the context of NWP and air pollution modeling
- Capturing urban thermal effects is important not only for PBL thermodynamics and also for wind field
- Preliminary results of urban models are encouraging, however, much work remains to be done
  - Refine urban canopy model
  - Need to explore two-way WRF/Noah/UCM and CFD coupling
  - Integrate fine-scale urban land use and characteristic data
- Plan an urban workshop in 2006

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Comprehensive Urban Modeling Framework

- Urban models
- Integrate new *in-situ* and remotely sensed data for better representing urban characteristics
- Integrate natural (biogenic, wildfire) and anthropogenic emissions
- High-resolution land data assimilation system
- Information transferable to decision support systems